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# THE INTEGRATION OF NEW TECHNOLOGY INTO A COMPLEX SYSTEM

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This paper describes an evaluation of the impacts of introducing change into the established complex system of UAS operations. Two technologies not currently used in UAS operations, a backup communications system and a traffic display, were operated by Guardian UAS pilots as they shadowed live UAS flights in a back-up control station. The flights were demonstration rather than research flights; we nonetheless were able to make the most of the opportunity and collect observation, survey, and interview data to gain insight into effects of the technology insertions. Technology-insertion impacts and recommended technology adaptations were categorized into emergent themes. The identified themes were found to align with three of the five basic generic support requirements for cognitive work proposed by Woods (2005, Generic support requirements for cognitive work: Laws that govern cognitive work in action. *Proceedings of the HFES 49th Annual Meeting*. Santa Monica, CA: HFES).

When changes are made to a complex system, effects can be difficult, if not impossible, to predict. Analysis and modeling are not likely to predict the effects of a change to a truly complex system. The best evaluation strategy may instead be to insert a change on a trial basis. Snowden and Boone (2007) describe this complex-systems strategy as inserting a *probe* so that the resulting emergent patterns can be assessed.

The main goal of the work described in this paper was to evaluate the effects of introducing into UAS operations two technologies, i.e., "probes", with potential to facilitate the integration of UAS into the national airspace system (NAS). One technology was a backup voice communications radio system to be used if a UAS pilot loses the voice communications link with air traffic control (ATC). UAS pilot communications with ATC are relayed via the aircraft so when the datalink connection with the aircraft is lost, voice communications are also lost. The second technology was an air traffic display (see Figure 1), which would provide UAS pilots with their only visual source of traffic information.


*Figure 1.* The Garmin GMX 200 traffic display used in the technology demonstration.

The technologies were introduced into UAS operations for the purpose of a technology demonstration. UAS pilots interacted with the technologies during staged *NAS events* while they shadowed the unfolding of live missions flown by two colleagues. The naturalistic setting helped pilots to consider the new technologies in terms of their relationships with the existing UAS operations system and their support for mission activities within the NAS.

# Methods

## Participants

Two UAS pilots stationed at Cape Canaveral Air Station (CCAS) volunteered to participate in the technology demonstration. Both read and signed informed consent documents. One pilot (*Pilot A*) had approximately 4,500 hrs as a UAS pilot and close to 2,000 hrs in general aviation aircraft. The other (*Pilot B*) had accrued approximately 500 hrs as a UAS pilot and 3,700 hrs flying military aircraft.

The pilots took turns as the *pseudo pilot* during each of three UAS missions flown by a pilot and sensor operator in a nearby ground control station (GCS). As pseudo pilot, the pilot sat in the operations center where he could monitor GCS radio communications and observe mission progress on displays identical to those in the GCS. One 2- to 3-hr mission was flown on each of three sequential days.

## Technology Additions

The backup communications system prototype was developed for the demonstration by Harris Corporation. The prototype consisted of a headset, user interface with voice-to-digital signal conversion, Jotron AM radio, and portable communications tower. The prototype's user interface featured a small screen, approximately 6 x 4 in (15.2 x 10.2 cm), positioned over a row of five function buttons and flanked on either side by system navigation controls.

The 4 x 3 in (10.2 x 7.6 cm) Garmin GMX 200 traffic display was attached to the upper right corner of a desktop monitor. The display featured icon representations of the UAS and surrounding traffic, directional information, and range rings (see Figure 1). Displayed aircraft 'tracks' were derived from ATC surveillance radar and transmitted via the Traffic Information Services-Broadcast (TIS-B) Service.

A desktop monitor to which the Garmin GMX 200 was attached displayed air traffic over a large section of the southeast United States. Evaluation team members used this display to gauge the accuracy of traffic data shown on the Garmin traffic display. Its position in front of the pseudo pilot may have interfered with assessing the Garmin traffic display, although data do not point to this.

## Procedure

The Guardian variant of the MQ-9 UAS (General Atomics Aeronautical Systems) flew a saw-toothed flight path off the central east coast of Florida (see Figure 2) on each of three demonstration flights. Altitude was maintained at 20,000 ft between the initial climb and final descent. The pilot in the GCS was asked to fly the prescribed route and was not given other taskings. Study participants assessed the mission plan as much simpler and easier than their typical mission.

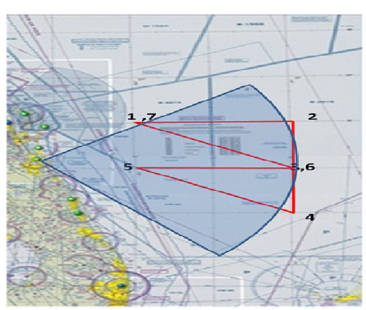


*Figure 2.* The mission flight path flown in the demonstration, indicated by red lines.

Pseudo pilots were seated in front of interfaces to the two new technologies. Immediately before the start of the first mission, pseudo pilots were familiarized with the technologies and shown how to use them. During each mission, two preplanned NAS events were presented to the pseudo pilots at Waypoint 3 and at three additional points spaced 10 min apart. The two events were always the same and represented events that could occur in the NAS. The pseudo pilots were instructed to imagine they were flying in the NAS when the events occurred.

In the first NAS event, pseudo pilots were told that the communication link with ATC was lost. The pseudo pilots used the backup communications system to re-establish communications, a task that culminated with a radio check to the local CCAS control tower. In the second NAS event, a veteran air traffic controller on the evaluation team issued a traffic call for traffic coming within 10 miles of the aircraft. (Distant live traffic was made to appear as if it was within 10 miles by treating range ring distances as if they represented smaller-than-actual distances.) The pseudo pilots used the Garmin CDTI to locate traffic and issued a verbal acknowledgement when they sighted it on their display.

In the operations center, a researcher seated behind the pseudo pilot observed and took notes. Because the pseudo pilots were not actually flying an aircraft, their workload was low enough that they could volunteer verbal feedback about the technologies over the course of each mission and immediately after each set of NAS events. The researcher captured this feedback in his or her notes.

After the first and third missions (participants were unavailable after the second mission), pseudo pilots completed a 20-item questionnaire and participated in a 1-hr semi-structured individual interview. The questionnaire consisted of 7-point-rating-scale and short-answer questions about the difficulty of the mission, ease and benefit of using the communications system, helpfulness and workload of the traffic display, and whether either technology changed their work. Interview questions had similar foci and asked pilots to describe their interactions with the technologies. The second interview, conducted after the third mission, revisited the questions asked after the first mission and then moved on to questions about past UAS missions for a different project. Interviews were tape recorded and subsequently transcribed.

## Results and Discussion

Observer notes, questionnaire responses, and interview transcripts were assessed to gauge effects of the inserted technologies on UAS operations. Data are summarized below in terms of benefits and recommended adaptations:

- *Benefits* – Benefits the pilots experienced or anticipated the technologies could offer.
- *Recommended adaptations* – Changes that should be made so the technologies better integrate with and support UAS operations.

In addition, recommended adaptations to the traffic display were coded using five *generic requirements for systems that support cognitive work* proposed by Woods (2005) and Elm, Potter, Tittle, Woods, Grossman, and Patterson (2005). This *thematic analysis* (Braun & Clarke, 2006) revealed patterns in traffic display adaptations that should improve the display’s integration into the complex cognitive UAS operations system. It additionally served as a check on the adequacy of the five generic requirements specified by Woods and his colleagues.

### Backup Communications System Effects on UAS Operations

Both pseudo pilots gave positive ratings (6s and 7s on the 7-point scale) of the backup radio system. They rated the system as easy to use and beneficial to the recovery of communications with ATC. Pilot A described his use of the system as “pretty seamless” and referred to it as the “most functionally promising" of the inserted technologies. Pilot B was similarly positive in his comments (e.g.: "if [the system] works as advertised, it will greatly increase our comms capability with ATC.") At the same time, the pilots were concerned that the technology might be dropped into their operations without first being integrated with their work or existing systems.

**Benefits.** Currently, a lost communications link means a UAS crew must call the ATC center via telephone, and someone other than the sector controller will answer that call. The pilots indicated that the new capability fills a gap by allowing them to re-establish communications with the sector controller within seconds. Pilot A suggested that the technology has the capacity to "expand our operations envelope and marginalize our risk…with proper integration and development."

**Recommended adaptations.** Noting that stress will be high during events that require the backup technology, Pilot A pointed out that "In order for us to pick up another headset and tune in another frequency…it's only going to add workload at a time when we're lost-comms and need all the efficiency in our HMI [human-machine interface] as possible." On the other hand, "if…channel selection… emulates the simplicity of the test, then that would be ideal." In other words, the pilots want the technology to be evaluated under more demanding conditions and in conditions for which the technology was not preconfigured. (The communications system was preconfigured for the demonstration flights.)

### Traffic Display Effects on UAS Operations

The pseudo pilots gave positive ratings (5 to 7 on a 7-point scale) of the traffic display's helpfulness and benefit to situation awareness (SA). Pilot workload associated with using the traffic display during a mission was rated as 4 and 5 ('1' signifies low workload) for the first mission. For the third mission, Pilot A gave a midrange rating of 4 and Pilot B came down to a 2. Pilot B attributed workload ratings to learning to manipulate a new piece of equipment (the CDTI). Pilot A attributed workload to a lack of integration with other displays.

**Benefits.** Both pilots viewed the traffic display as useful for maintaining awareness of their aircraft's position relative to its surroundings and planning ahead. Pilot B additionally said he would use the traffic display to communicate UAS position and path to ATC as part of a lost-link procedure. Pilots described using the display to obtain "overall SA" and for "response to and identification of ATC-directed targets" (Pilot A) and as a means to "enhance…overall situational awareness" (Pilot B).

**Recommended adaptations.** Responses to inserted events revealed that communications protocols associated with use of the traffic display need attention. The current protocol that pilots use to reply to traffic calls assumes the pilot can see traffic directly, versus only as an icon on a display. New phraseology should additionally address a concern voiced by Pilot B; specifically, how to establish that a track the pilot is "seeing" and confirming is the same track ATC called out.

Whereas the pilots found the traffic display to enhance SA and "big-picture awareness" of the Command Duty Officer (CDO; oversees and coordinates UAS missions), they reported it to be of limited value for tactical, close-in traffic avoidance by pilots. Pilot B stated the display would be valuable to him in the role of CDO, but that "in the GCS, I've got enough screens and buttons to push. I've got enough to do. It's something I wouldn't do. I wouldn't be interested in it when I'm flying."

### Thematic Analysis of Recommended Traffic Display Adaptations

Pilot interview data and short-answer survey responses were synthesized into 16 specific recommendations for traffic display adaptation. These recommendations were coded using the five generic requirements for system designs that support cognitive work and examples Woods, Elm and their colleagues use to define each code (Elm et al., 2005; Woods, 2005). Codes and the number of display adaptation recommendations assigned to each are shown in Table 1.

Table 1.
*The Number of Recommended Traffic Display Adaptations Assigned to Cognitive-Work-Support Codes*

| Generic Cognitive Work Support Codes | | Number of Recommendations |
|---|---|---|
| **Generic Requirements** | **Requirement helps the operators in a system to…** | |
| Observability | gain insight into system processes. | 1 |
| | avoid keyhole effect. | 1 |
| | see sequences. | 2 |
| | see future activities and contingencies. | |
| | see patterns and relationships in a process. | 3 |
| Directability | direct/re-direct resources in response to and anticipation of changes in the environment. | 3 |
| | direct/re-direct activities. | |
| | direct/re-direct priorities. | 1 |
| Teamwork with Agents; Shifting Perspectives | establish teamwork (with human and automated teammates) | |
| | coordinate and synchronize activity across agents. | |
| | redirect teammates by seeding new ideas, reminding, and critiquing as a situation changes. | |
| Directed Attention | reorient attention in a changing environment. | 3 |
| | track teammates' focus of attention. | |
| | judge interruptibility of teammates. | |
| Resilience | use failure-sensitive strategies (via feedback). | |
| | explore outside current boundaries or priorities. | |
| | step in to support brittle automation. | |
| | maintain peripheral awareness. | |
| Other | interpret symbols and alarms. | 2 |

**Patterns in Recommended Adaptations.** Pilots' recommendations for adapting the traffic display mainly involved supporting perception and cognition in a dynamic information-rich environment. The pilots wanted information presented in ways that support a majority of the *observability* goals (i.e., ways observability supports complex cognitive work) listed in the first 5 rows of Column 2 in Table 1. They also wanted to have continuous control over the information they viewed; specifically, they wanted to be able to visually segregate, flag, and adapt displayed information. The third main category of recommendations involved changes to improve pilots' ability to perceive and process important traffic information without removing their attention from other aspects of their work.

**Implications for the Generic Requirements for Supporting Cognitive Work.** We were able to map all traffic display recommendations to the generic system requirements for supporting cognitive work with just two exceptions. Those two exceptions were related to improving the interpretability of symbols and alarms (see the last row of Table 1) and are relevant to the observability requirement in that they make observability goals possible. In addition, three recommendations that mapped to the generic requirement *directability* did not clearly map at the goal level. These recommendations were coded as *direct/re-direct resources*; however, the resources in these recommendations were traffic display information elements, which are not typically considered work-system resources. This category of recommendation can continue to be treated as a resource or it might suggest the need for an additional directability goal: the goal of helping the operator in a system *direct/re-direct the form and content of a system's human-technology interfaces*.

## Conclusions

Adding new technology to a complex system can introduce perturbations and interactions that, in effect, negate the technology's intended benefits. By revealing ways to align safety-enhancing technologies with the UAS operations system, including pilots' cognitive work, the demonstration described in this paper contributes to a reduced risk of unintended consequences.

According to complexity science, a system develops resilience when its parts are permitted to co-evolve (e.g., Bar-Yam, 2004; Benbya & McElvey, 2006). In this effort, UAS pilots were given new technologies to use while responding to inserted NAS events as they shadowed live UAS operations. By combining these system elements (pilots, new and existing technologies, NAS events, and UAS mission activities), we gained insight into ways they can co-evolve and become more attuned with each other.

This work contributes to the study and design of complex systems by evaluating five proposed generic requirements for systems that support cognitive work (Elm et al., 2005; Woods, 2005). Support was found for three of the five requirements and no evidence was found to conflict with any of the five. Findings suggest that information interpretability might be added as a sixth requirement, although that requirement might be better suited to the body of traditional human-computer interface design guidelines than to Woods' and Elm et al.'s five generic requirements. Data also suggested that the directability requirement be extended to include directability of the human interfaces to system elements and activities in addition to directablity of system elements, activities, and priorities.


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